Original Article

Biomechanical Effects of Fixed Functional Appliance on Craniofacial Structures

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ABSTRACT

Objective: To evaluate displacement and stress distribution on craniofacial structures associated with fixed functional therapy.

Materials and Methods: A finite element model of the human skull was constructed from sequential computed tomography images at 2-mm intervals using a dry adult human skull. In this study, linear, four-nodal, tetramesh and triangular shell elements were used with six degrees of freedom at each of their unstrained nodes: three translations (x, y, and z) and three rotations (around the x-, y-, and z-axes).

Results: The entire mandible moved anteroinferiorly. Maximum displacement was observed in the parasymphyseal and midsymphyseal regions. The pterygoid plate was displaced in a posterosuperior direction. The anteroinferior displacement of the mandibular dentition was most pronounced in the incisor region, while the maxillary dentition was displaced posterosuperiorly. The entire dentition experienced tensile stress except for the maxillary posterior teeth. Tensile stress was also demonstrated at point A, the pterygoid plates, and the mandible, and minimal compressive stress was demonstrated at anterior nasal spine. Maximum tensile stress and von Mises stresses occurred in the condylar neck and head.

Conclusion: Fixed functional therapy causes a posterosuperior displacement of the maxillary dentition and pterygoid plate and thus can contribute to the correction of Class II malocclusion. The displacement was more pronounced in the dentoalveolar region as compared to the skeletal displacement. All dentoalveolar structures experienced tensile stress, except for anterior nasal spine and the maxillary posterior teeth. (*Angle Orthod.* 2009;79:668–675.)

KEY WORDS: Fixed functional appliance; Stress; Displacement

INTRODUCTION

Fixed functional appliances are effective in the management of Class II malocclusion. This is the only successful bite-jumping treatment for noncompliant, postpubertal patients that does not require orthognathic surgery at a later stage.[1–3] Fixed functional appliances are reported to correct Class II skeletal problems by encouraging mandibular growth and by eliciting dentoalveolar effects.[4–6]

Mandibular displacement was first demonstrated by Herbst[7] in 1934. Further clinical and cephalometric studies have supported this finding.[7–12] These studies have shown an anterior displacement of the mandible and a posterosuperior displacement of the maxilla similar to the effects seen from headgear treatment.[7–12] Hu et al[13] and Zhou et al[14] reported tensile stress in the posterior condylar region with compressive stresses in the anterior region. The changes in the condyle are assumed to be a result of mechanical stimulus of the fibrocartilage layer of the condyle, such as for long bones with similar structure.[15–18] Thus the stress from fixed functional appliances should be studied to further explore the association with morphologic changes of the dentoalveolar complex. These investigations will help to further elucidate the mechanism of remodeling of the mandible and provide clinical indications for fixed functional appliance therapy.

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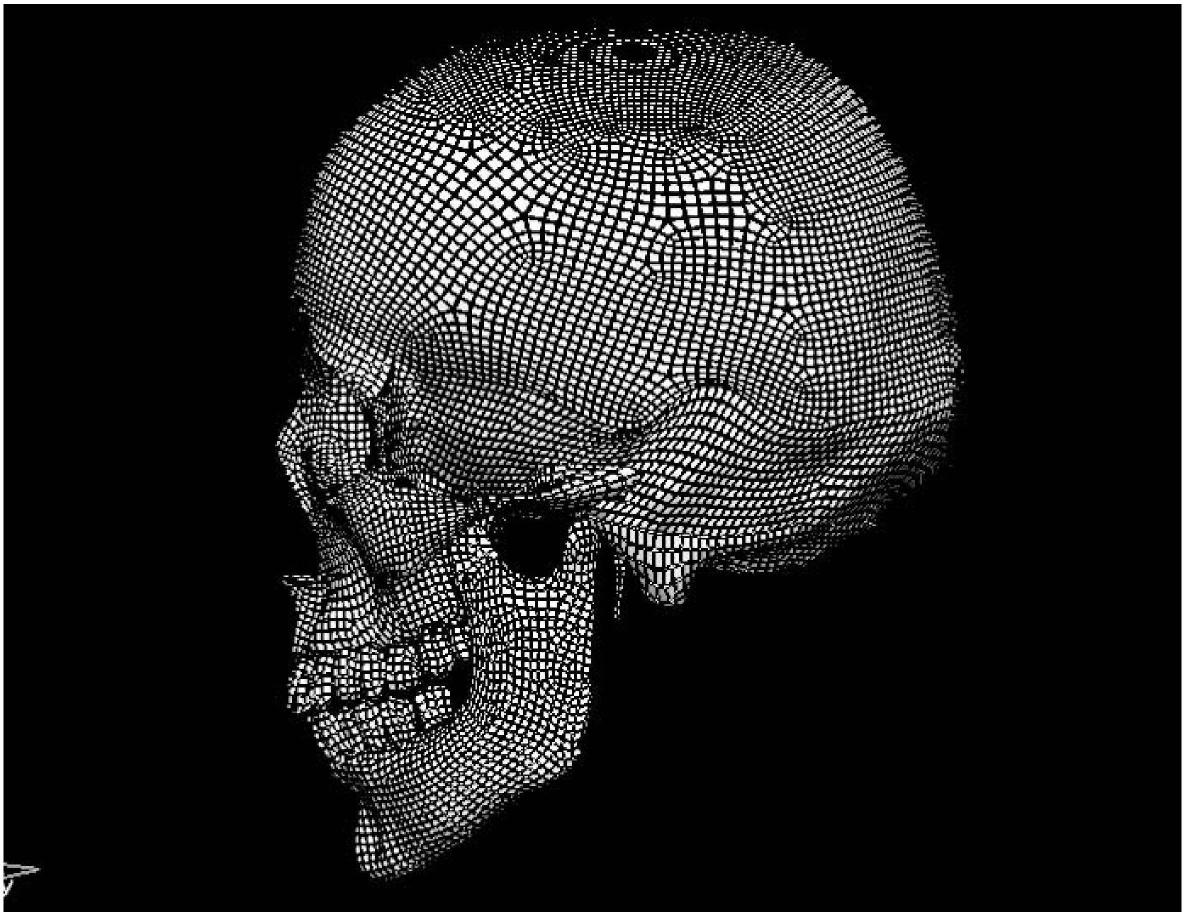

Figure 1. Three-dimensional finite element model of dried adult skull.

Although many clinical studies have investigated the displacement and stress caused by fixed functional treatment, a recent study by Ulusoy and Darendeliler[19] tried to quantify and explain the stress distribution pattern.[12–17] Finite element models (FEMs) have been successfully used to study stress and strain, making it practicable to show stress distribution and displacement in living structures as induced by various appliances.[20] The present FEM study was designed to investigate the displacement and stress distribution exerted by a fixed functional appliance on various craniofacial structures.

MATERIALS AND METHODS

The present analytical model was developed from a dried adult human skull with the mandible and intact permanent dentition and without any gross defects or discontinuity in the anatomy. Computed tomographic (CT) scan images of the skull were made in the axial direction at 2-mm intervals in the horizontal plane. The individual CT scan sections were traced on acetate paper enlarged 400 times to the original skull size. This was traced onto graph paper for digitization using Microsoft Image Pro-Plus software. These tracings were later imported into AUTOCAD engineering software version 2004 (Autodesk Inc, San Rafael, Calif) for modeling and saved in .iges (integrated graphics exchange system) format.

The FEM programs used in this study were Altair Hypermesh version 7 (Altair Engineering Inc, Troy, Mich) and FE-MAP, (NEi Nastran Software, Inc, Westminister, CA) which were run on a personal computer with a graphics accelerator. Only half of the cranium, with respect to the sagittal plane, was modeled and analyzed, as this would produce the same results as a scan of the complete skull. The geometric entities created in the previous step were meshed into finite elements and nodes (Figure 1).

The complete geometry is defined as an assemblage of discrete pieces called elements, which are connected together at a finite number of points called nodes. In this study, linear, four-nodal, tetramesh and triangular shell elements were used, which were able to take membranes into account, ie, in-plane deformation as well as bending deformations. The shell elements had six degrees of freedom at each of their

Table 1. Young's Modulus and Poisson's Ratio of Various Materials Used in the Study[20,21]

Material	Young's Modulus (kg/mm²)	Poisson's Ratio
Tooth	2.0×10^3	0.15
Compact bone	1.37×10^3	0.15
Cancellous bone	7.93×10^2	0.15

unstrained nodes: three translations (x, y, and z) and three rotations (around the x-, y-, and z-axes). The total number of elements and nodes created were 13,590 and 18,582, respectively.

The material properties of the bone and teeth in the model were defined according to experimental data from previous studies (Table 1).[21,22] Constraints were applied at all other nodes of the cranium lying in the symmetrical plane, and appropriate boundary conditions were imposed. In addition, a zero-displacement and zero-rotation boundary condition was imposed on the nodes along the foramen magnum.

The maxillary and mandibular dentition was consolidated into two separate units to simulate the clinical situation. The forces generated by fixed functional appliances vary from 150 to 200 g (1.47 to 1.98 N).[10,23] Hence, in the present study, forces of 2 N were applied to simulate the application of a fixed functional appliance between the maxillary molars and the mandibular anterior segment (Figure 2). The displacements, von Mises stresses, and principal compressive stresses were studied. The stress distribution patterns were analyzed, and the results were tabulated and represented graphically.

Table 2. Displacement of Various Craniofacial Structures (in mm)[a]

Parameter	Minimum	Maximum	Mean
Dentition			
Maxillary anterior	−0.00155	−0.00207	−0.00181
Maxillary posterior	−0.00155	−0.00207	−0.00181
Mandibular incisors	0.00777	0.00828	0.008025
Mandibular canines	0.00725	0.00828	0.007765
Mandibular premolars	0.0057	0.00673	0.006215
Mandibular molars	0.00414	0.00581	0.004975
Nasomaxillary complex			
ANS	0.00104	0.00155	0.001295
Point A	0.00207	0.00311	0.00259
Pterygoid plates	−0.000518	−0.00104	−0.000779
Mandible			
Midsymphyseal	0.00822	0.00935	0.008785
Parasymphyseal	0.00777	0.00828	0.008025
Center of body	0.00466	0.00518	0.00492
Coronoid	0.00311	0.00362	0.003365
Neck of condyle	0.00104	0.00155	0.001295
Condylar head	0.000518	0.00104	0.000779

[a] Positive value indicates an anterior movement in the sagittal (y) plane and an upward movement in the vertical (z) plane. Negative value indicates a posterior movement in the sagittal (y) plane and a downward movement in the vertical (z) plane.

RESULTS

The biomechanical changes observed in this study are shown in Tables 2 and 3 and Figures 3 through 5.

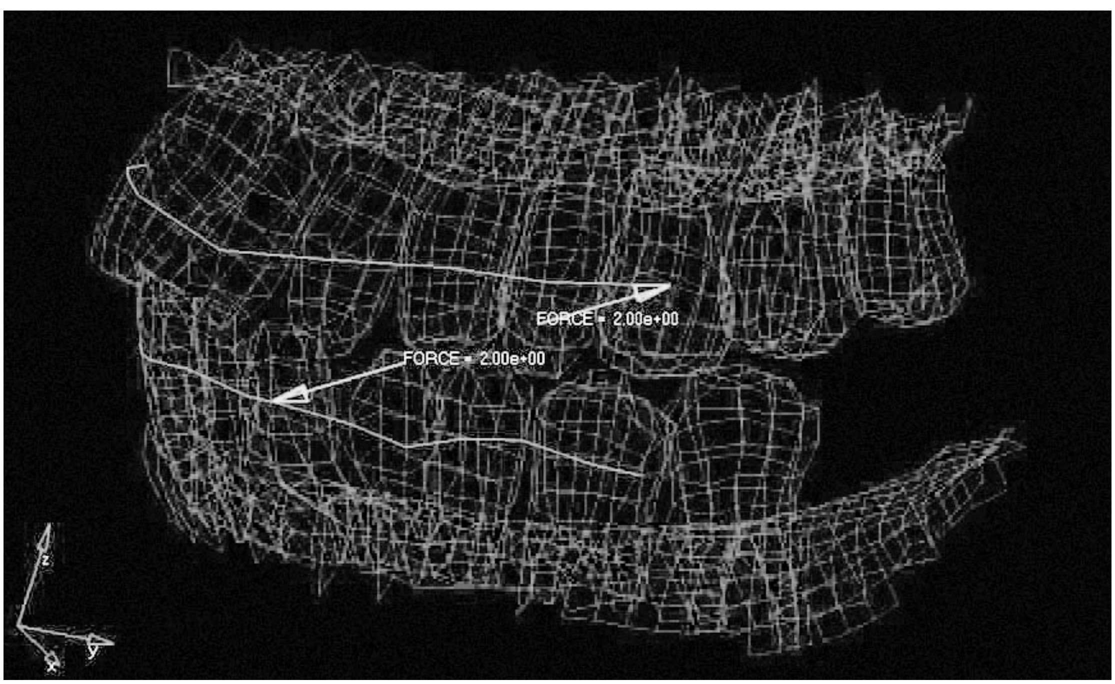

Figure 2. Force application (2 N) on the archwire simulates a fixed functional appliance.

Table 3. Principal Stress Distribution of Various Craniofacial Structures (in MPa)[a]

Parameter	Minimum	Maximum	Mean
Dentition			
Maxillary anterior	0.307	0.676	0.4915
Maxillary posterior	−0.676	−1.786	−1.231
Mandibular incisors	0.676	1.416	1.046
Mandibular canines	1.416	1.786	1.601
Mandibular premolars	1.416	1.833	1.6245
Mandibular molars	1.046	1.183	1.1145
Nasomaxillary complex			
ANS	−0.307	−0.433	−0.37
Point A	−0.0632	0.307	0.1219
Pterygoid plates	0.307	0.676	0.4915
Mandible			
Midsymphyseal	0.307	0.676	0.4915
Parasymphyseal	0.449	0.700	0.5745
Center of body	1.046	1.786	1.4166
Coronoid	0.307	1.046	0.6765
Neck of condyle	4.376	4.744	4.56
Condylar head	4.178	4.698	4.438

[a] Positive value (+) indicates tensile stress and negative value (−) indicates compressive stress.

Table 2 and Figure 3 illustrate the displacement of various craniofacial structures. The principal stresses and von Mises stresses are shown in Table 3 and Figures 4 and 5.

Displacement

The entire mandible displaced in the forward and inferior directions, with the parasymphyseal and midsymphyseal regions showing a more pronounced displacement than the rest of the mandible (Figure 3). In the nasomaxillary complex, the nodes representing point A and anterior nasal spine (ANS) were displaced anterosuperiorly, but those representing the pterygoid plate were displaced in the posterosuperior direction (Figure 3, Table 2).

The clockwise rotation of the mandible was accompanied by anteroinferior displacement of the entire mandibular dentition. This side effect was greatest in the incisor region (Table 2). The maxillary dentition was displaced in the posterosuperior direction (Table 2).

Stress Distribution

The pattern of stress distribution differed among the various craniofacial structures (Figures 4 and 5). Tensile stress was experienced by the entire dentition except for the posterior maxilla, which experienced compressive stress (Table 3).

The principal stress examined in the nasomaxillary complex demonstrated tensile stress in point A and the pterygoid plate, but a minimal compressive stress was

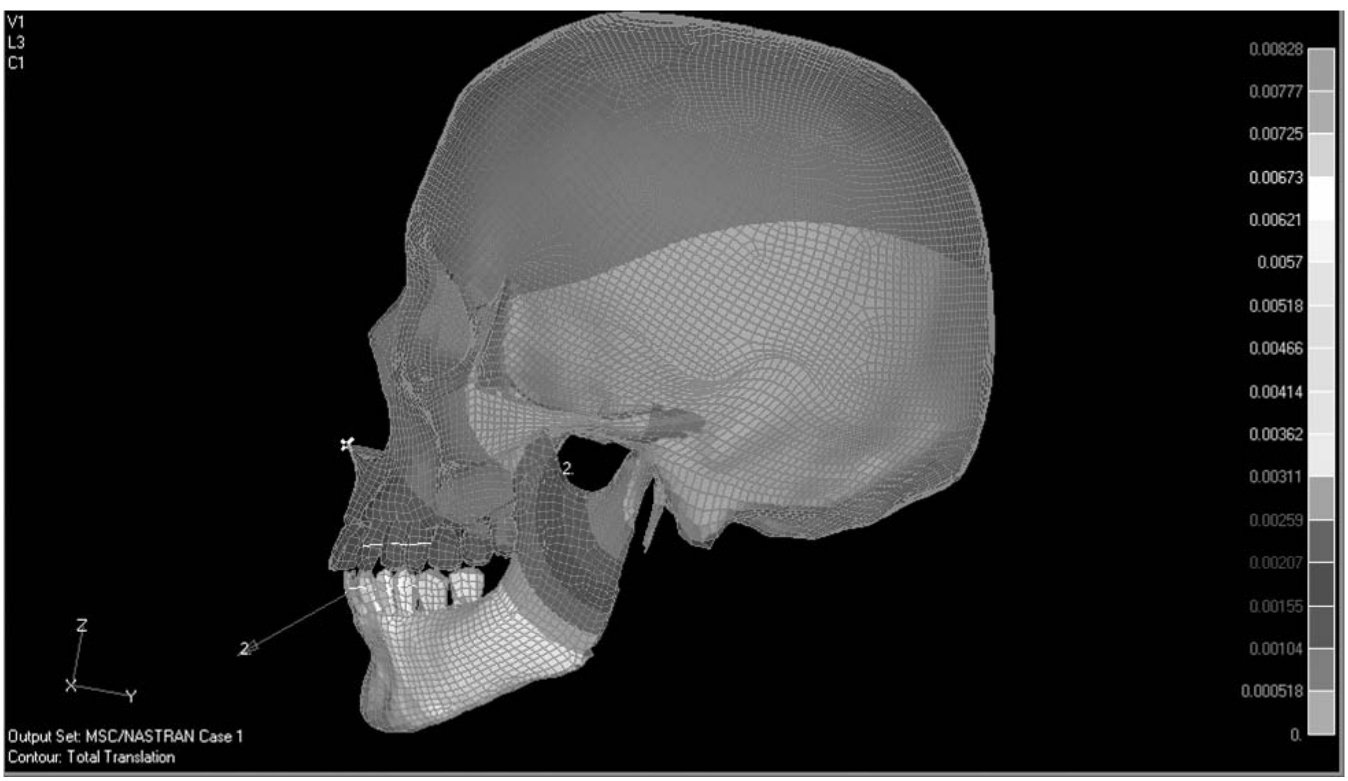

Figure 3. Displacement pattern (in mm) of craniofacial structures a with fixed functional appliance.

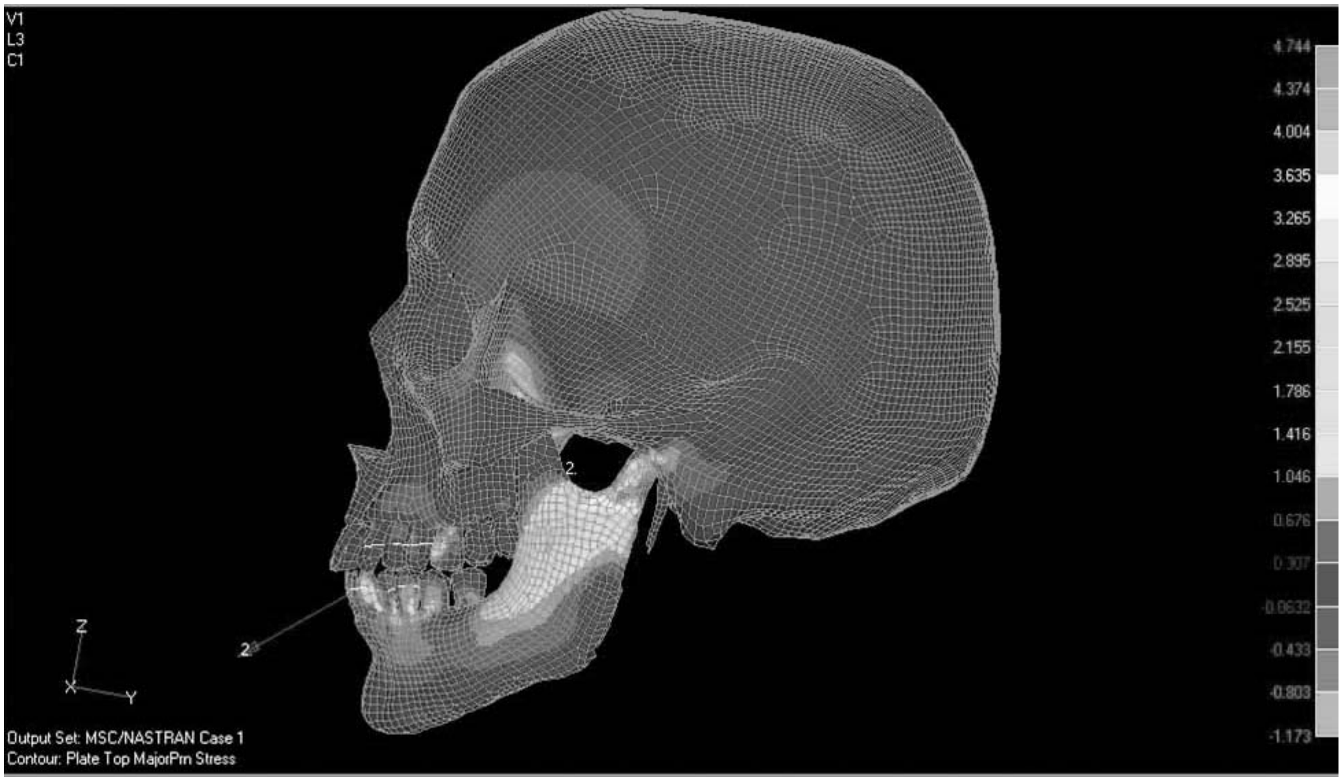

Figure 4. Pattern of stress distribution (in MPa) in the craniofacial structures.

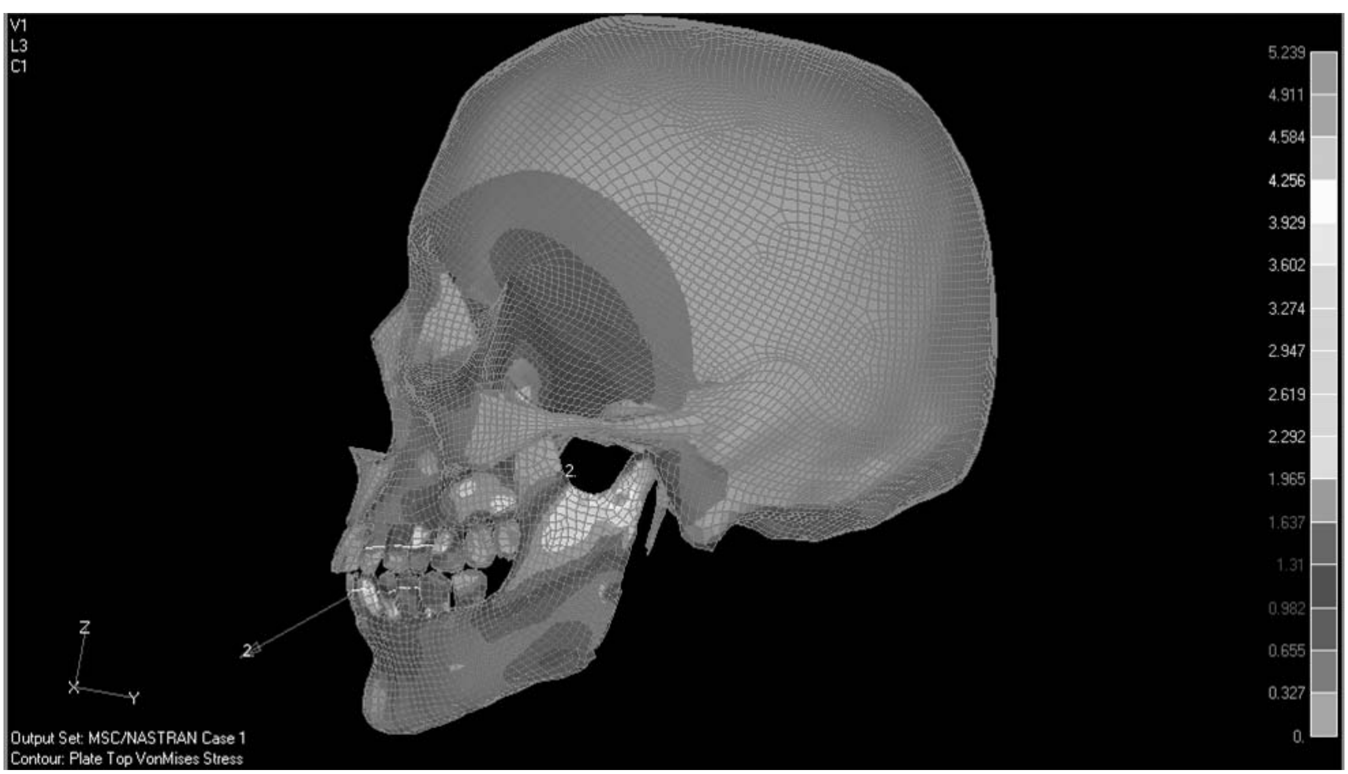

Figure 5. Pattern of von Mises stress distribution (in MPa).

Table 4. von Mises Stress Distribution of Various Craniofacial Structures (in MPa)

Parameter	Minimum	Maximum	Mean
Maxillary anterior	0	0.327	0.1635
Maxillary posterior	0.982	2.619	1.8005
Infratemporal fossa	1.31	2.292	1.801
Midsymphyseal	0	0.327	0.1635
Center of body	0.982	1.965	1.4735
Coronoid	0	0.327	0.1635
Neck of condyle	4.584	5.239	4.9115
Condylar head	2.619	4.584	3.6015

seen in ANS. Stress induced in the entire mandible was tensile in nature. Maximum tensile and von Mises stresses were reported in the condylar neck and condylar head (Tables 3 and 4). However, other areas demonstrated minimal von Mises stresses (Figure 5).

DISCUSSION

In the present study, we validated our results in comparison with previously published human studies, as direct validation was not possible. Previously published human studies had reported only displacement.[8–12] The present study assessed displacement and the distribution of stress on various craniofacial structures.

Displacement

In clinical practice, a Class II correction is attained via fixed functional appliances, which induce skeletal and dental changes.[4,8–12] Most of the studies carried out on fixed functional appliances have reported a greater dentoalveolar effect.[23–32] Our study reported a similar observation.

A limited restraining effect on the downward and forward growth on the maxilla was demonstrated (Figure 3). Nalbantgil[23] reported this to be the only skeletal effect that took place during Jasper Jumper therapy. A posterosuperior displacement of the maxillary jaw base (telescopic mechanism) was demonstrated in the present study. This is a result of a posterosuperiorly directed force on the maxillary jaw base.[23] This telescopic mechanism has also been reported by other investigators.[9,24–27]

Weiland and Bantleon[28] reported a minimal posterosuperior displacement of the pterygoid plate. They further concluded that the changes at point A were a result of retrusion of the maxillary incisors. Our study showed a similar effect on the maxillary dentition. The retrusion and extrusion of maxillary incisors and the distalization and intrusion of the maxillary molars seen in the present study (Table 2, Figure 3) also have been reported by several investigators. In addition, they have reported a downward tipping of the occlusal plane in the anterior region.[9,25–32] Pancherz[8,9] showed similar orthopedic and distalizing effects. This is in contrast to our study, where a greater distalizing effect was observed. Some investigators also reported a downward tipping of the palatal plane and occlusal plane.[9,26–29] However, in the present study, a rotational effect on the palatal plane could not be established, as posterior nasal spine was not considered. Point A and ANS, however, remodeled in the upward and forward directions, in contrast to reports by other authors.[28–32] We observed an anteroinferior displacement of the mandibular dentition pointing to a clockwise rotation. This displacement has also been documented by Cope et al,[25] Covell et al,[26] and Weiland and Bantleon.[28] Proclination of the mandibular incisors was the most pronounced dental side effect reported in the present study. Several cephalometric studies have supported this finding, although there were variations in the extent of this effect.[8–10,25–31] Oliveira et al[24] reported a significant mesial migration of the mandibular molars during Herbst treatment, very similar to our findings (Table 2).

The entire mandible rotated in the forward and downward directions (Figure 3). Stucki and Ingervall[29] and others[25–27] demonstrated an increase in mandibular length. The greatest displacement, seen in the parasymphyseal and midsymphyseal regions in the present study, correlated with the chin improvement shown by various cephalometric and clinical studies.[7–12,25–29] The anterior condylar displacement seen in the present study was also reported by Pancherz,[4,8] who reported posterior rotation of the mandible. This could account for the increased vertical dimension seen during Herbst treatment.

Stress Distribution

FEM can be used as an analytical model with standard shape and mechanical behavior.[21,22] Therefore the results obtained provide insight into stress distribution of the craniofacial structures during fixed functional treatment (Figures 4 and 5 and Tables 3 and 4).

Experimental studies on morphologic changes of the mandible have shown that condylar pull results in significant mandibular growth.[15,18,32] This pull causes tensile stress along the viscoelastic tissue and muscle tendons attaching to the fibrocartilage of the condyle, which is responsible for condylar growth.[15] Graber[33] and Joho[34] reported that compressive stress in the condyle led to decreased condylar glenoid fossa modification.[33,34] This is in contrast to Takano et al,[35] who found increased bone remodeling owing to increased synthesis of DNA and glycosaminoglycans. Biomechanical studies have shown that principal stress is crucial in the remodeling of alveolar and craniofacial bone.[23–25] Further histologic studies have shown the association of stretched viscoelastic tissue and bone remodeling.[15]

The principal stress distribution given in Figure 4 suggests tensile stress throughout the dentoalveolar structures, except for ANS, which experiences minimal compressive stress. The tensile and von Mises stresses were greatest in the condylar neck and condylar head (Figures 4 and 5 and Tables 3 and 4). It could not be determined whether these values were within the optimal range. Histologic studies by Ress[36] have shown attachment of the tendons of the lateral pterygoid, masseter, and temporalis muscles to the condylar neck and condylar head. Thus the isometric contraction of these muscles during bite jumping may lead to the increased tensile stress experienced by the condylar neck and head. However, other studies have reported decreased postural electromyographic muscle activity during treatment.[37–40] The growth relativity hypothesis could provide another explanation.[15] According to this, the stretched posterior viscoelastic tissue (tendons of temporomandibular joint, fibrocapsule, and retrodiscal tissue) between the condyle and glenoid fossae leads to bone remodeling during bite jumping. This may result in the maximum tensile stress seen in the condylar head and condylar neck. Zhou[14] and Hu[13] observed increased tensile stress in the posterior condylar region, which supports the present findings. However, in the present study, no definitive correlation could be established because of the limitation of the present FEM, which only considered hard tissue established by the CT scan. The compressive stress seen in ANS and the posterior maxilla may be responsible for the headgear effect that was apparent in various clinical and cephalometric studies.[9–12,27–32]

Clinical Considerations

Fixed functional appliances facilitate the forward and downward displacement of the mandible. They also cause a posterosuperior displacement of the maxillary dentition and pterygoid plate and thus contribute to the correction of a Class II malocclusion. Mandibular incisor proclination is the most pronounced dentoalveolar side effect seen during fixed functional treatment.[4,8,27–31] This is a matter of concern in patients, as it increases relapse tendency and also limits skeletal and soft tissue correction.[4,27–31] This could be prevented by cinching the mandibular archwire and laceback in the mandibular arch and by incorporating progressive lingual crown torque in the mandibular anterior segment.[4,8,27–31] Inclusion of the second molars during treatment could enhance anchorage and prevent unwanted proclination of anterior teeth. In high-angle patients, fixed functional appliances should be avoided, as this may increase the vertical dimension owing to clockwise rotation of the mandible.[4,7,8]

CONCLUSION

- The displacement resulting from fixed functional therapy was predominantly dentoalveolar in nature.
- Forward and downward displacement of mandibular incisors was the most pronounced dentoalveolar effect, followed by mandibular molar displacement.
- The mandible rotated in the forward and downward direction, but the pterygoid plate and maxillary dentition demonstrated posterior and superior displacement similar to that seen with the use of headgear.
- Tensile stress was found in the entire dentoalveolar structure, except at ANS.
- Maximum tensile and von Mises stresses were found in the condylar neck and condylar head.

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